(54) **METHOD AND APPARATUS FOR A JONES VECTOR BASED HETERODYNE OPTICAL POLARIMETER**

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(57)　　　　　　　　**ABSTRACT**

A heterodyne polarimeter is disclosed where a polarization state is measured by using a polarization diversity receiver employing a polarization beam splitter to output two heterodyne signals. The amplitude and relative phase of the two detected heterodyne signals uniquely determine the polarization state.
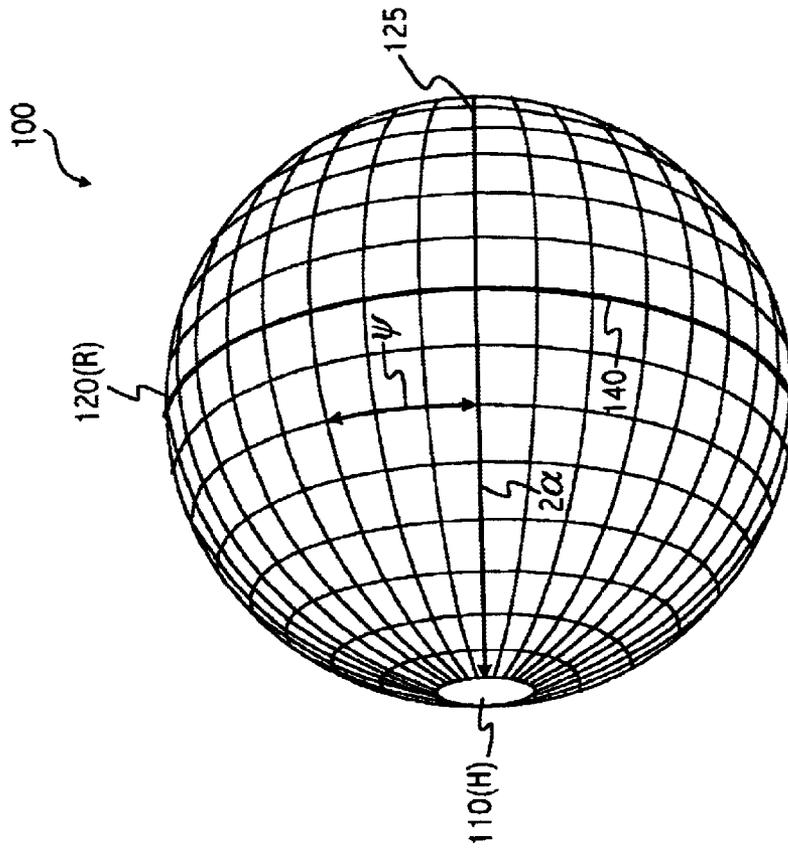
20 Claims, 13 Drawing Sheets
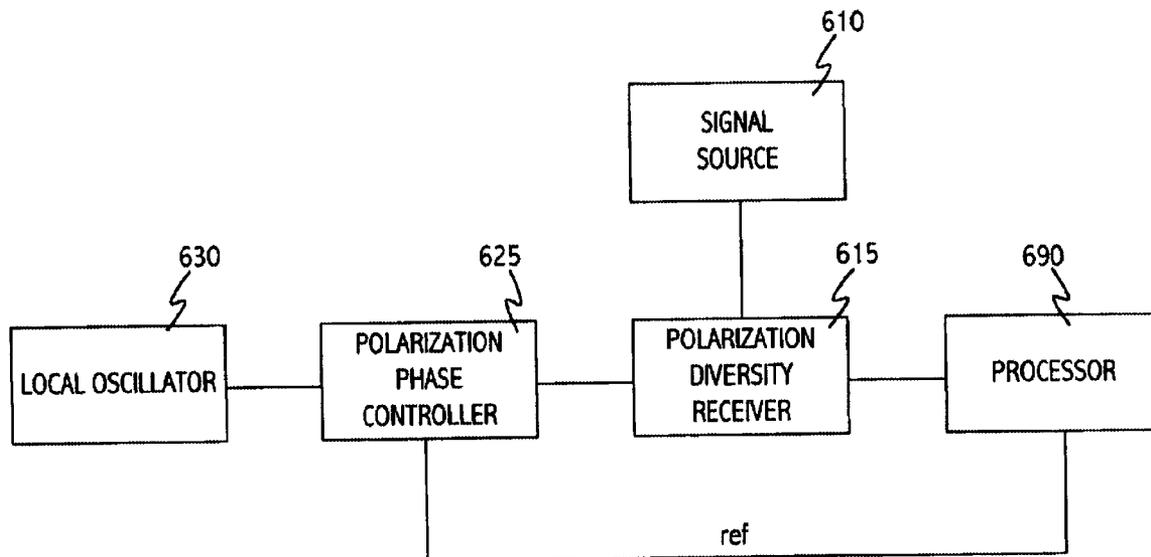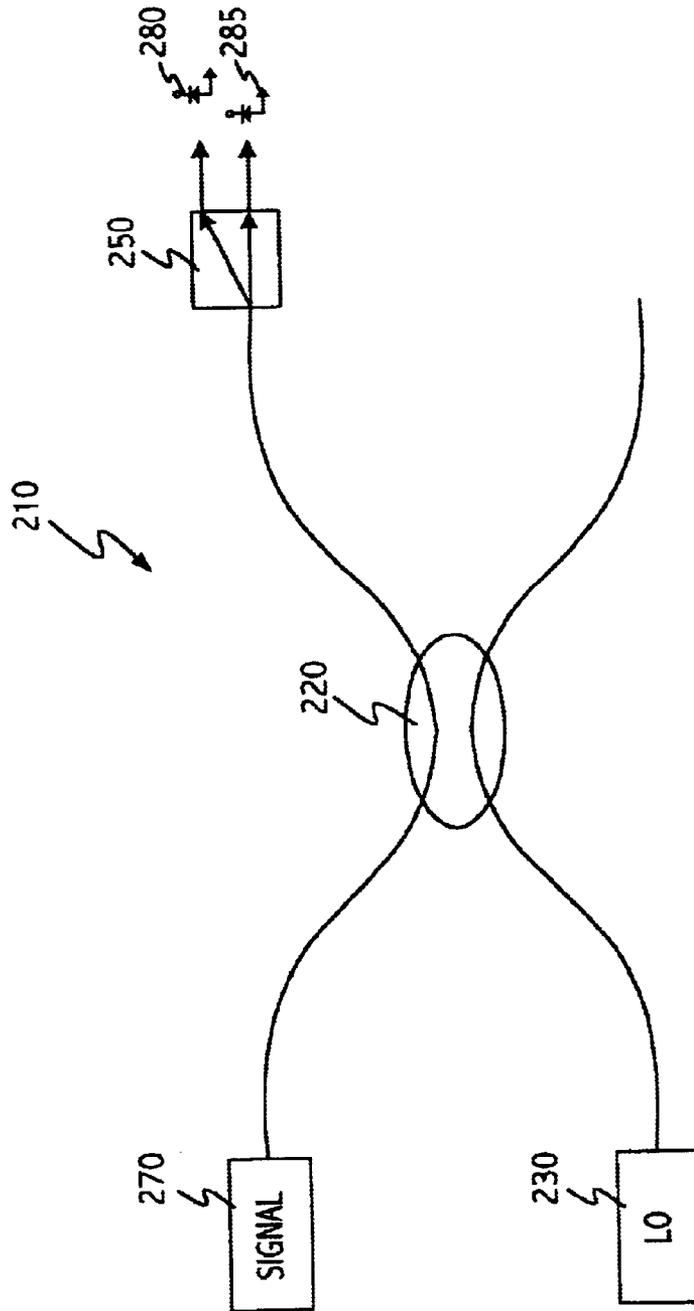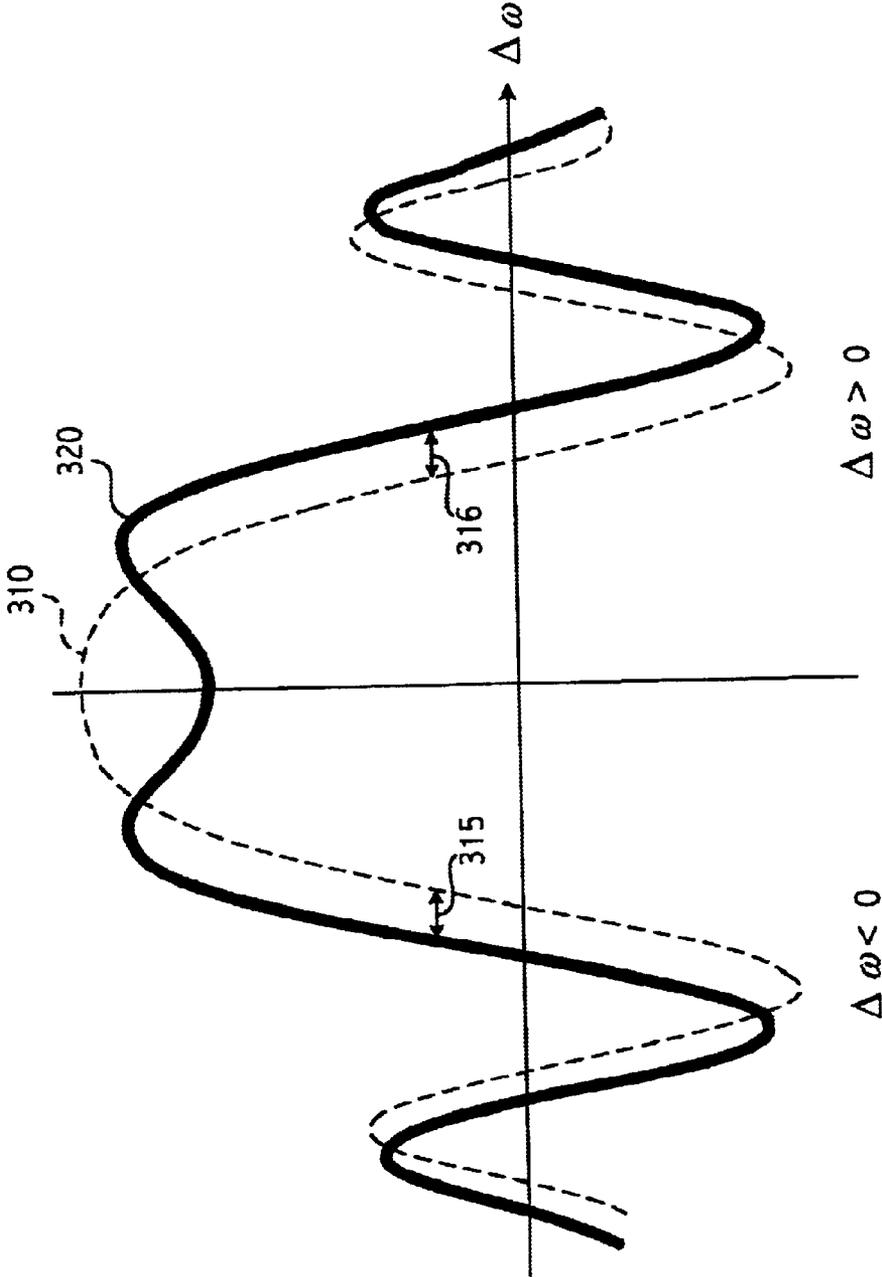
FIGURE 1

FIGURE 2

FIGURE 3
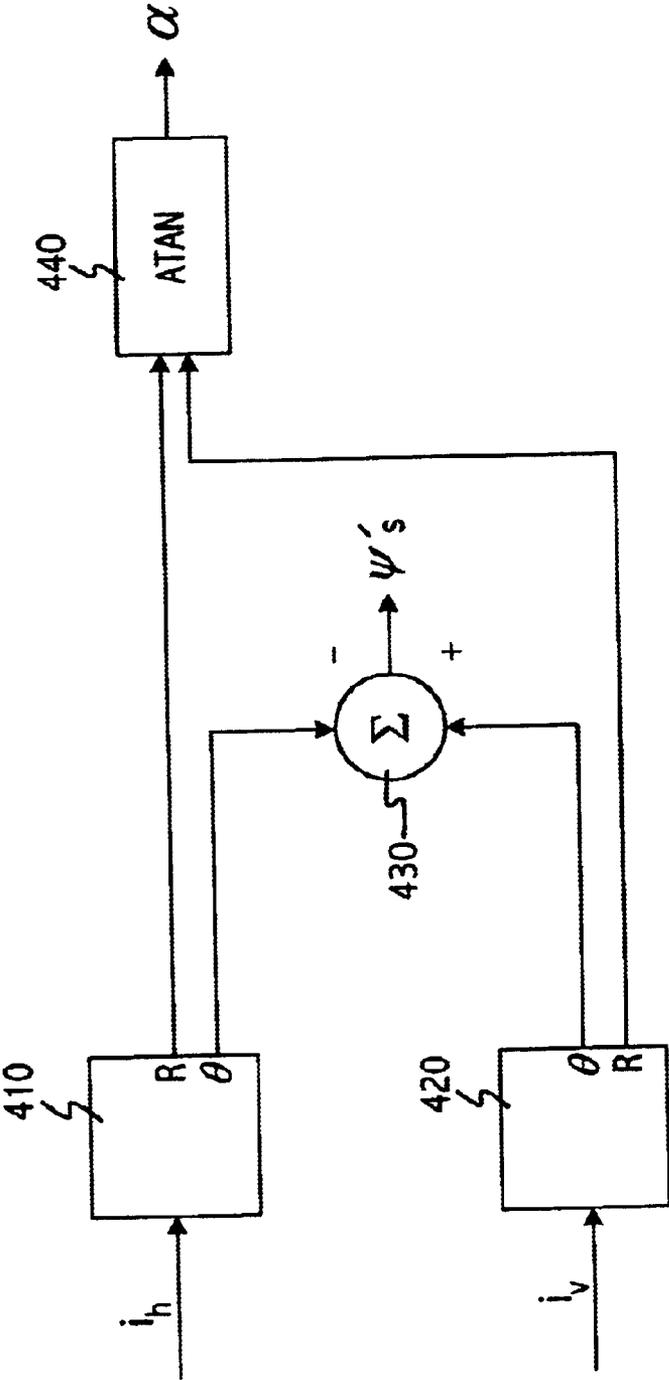
FIGURE 4
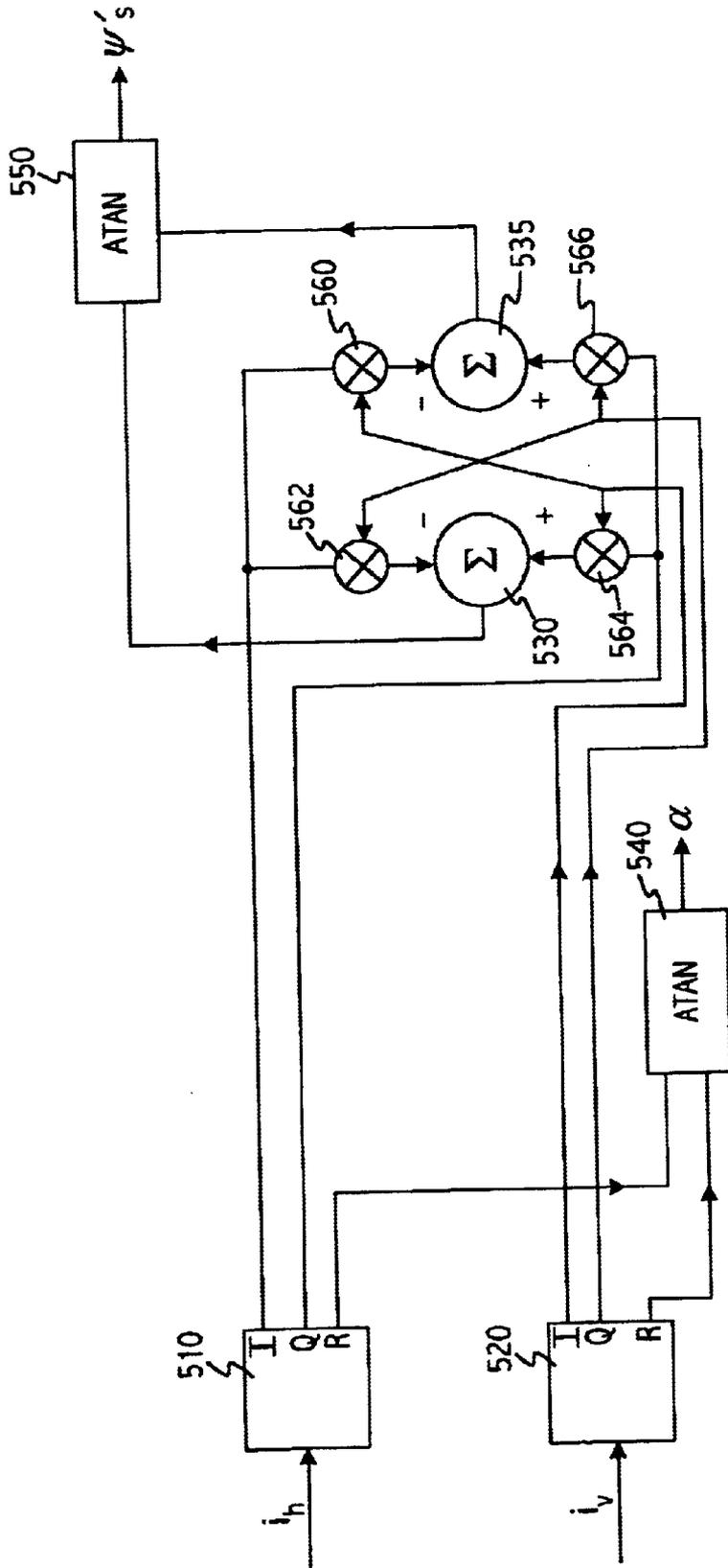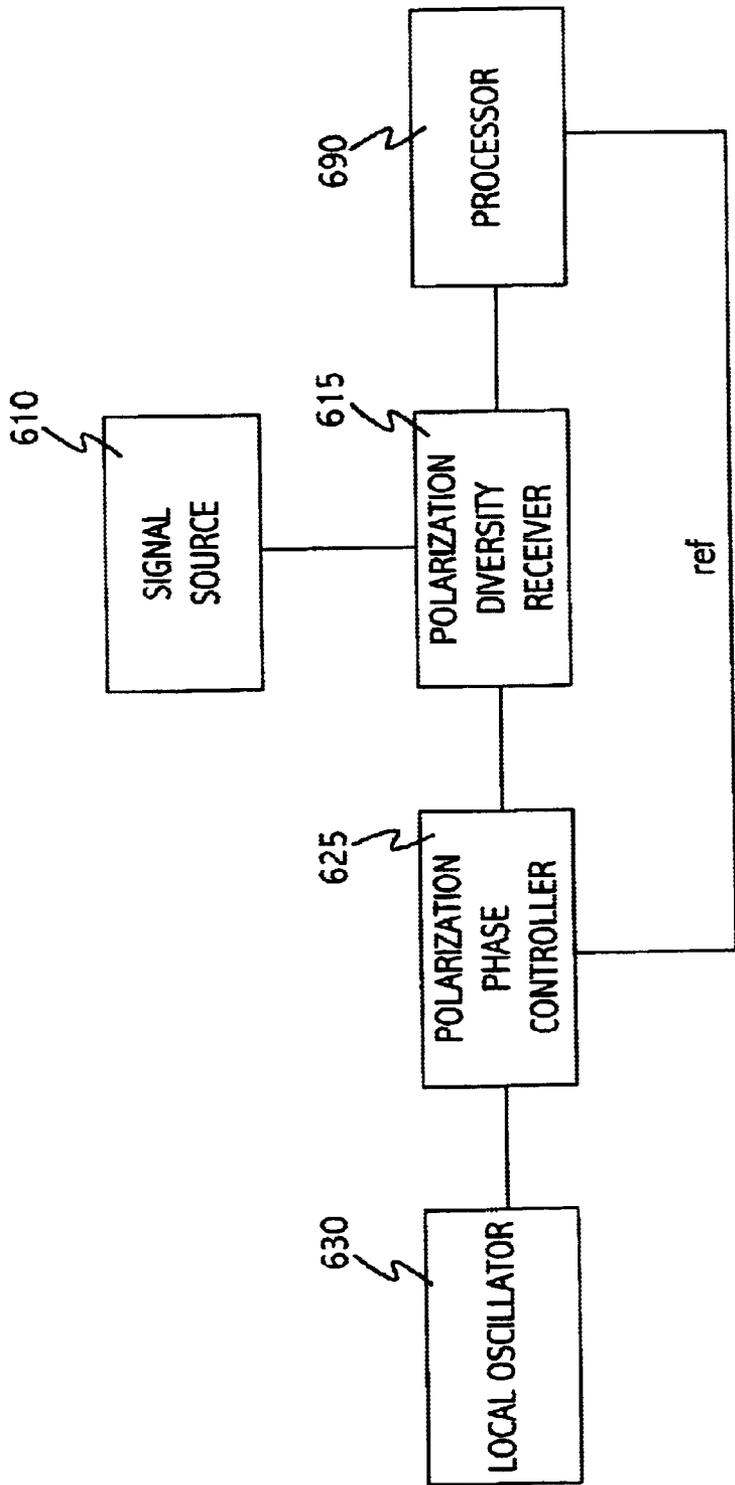
FIGURE 5

FIGURE 6A
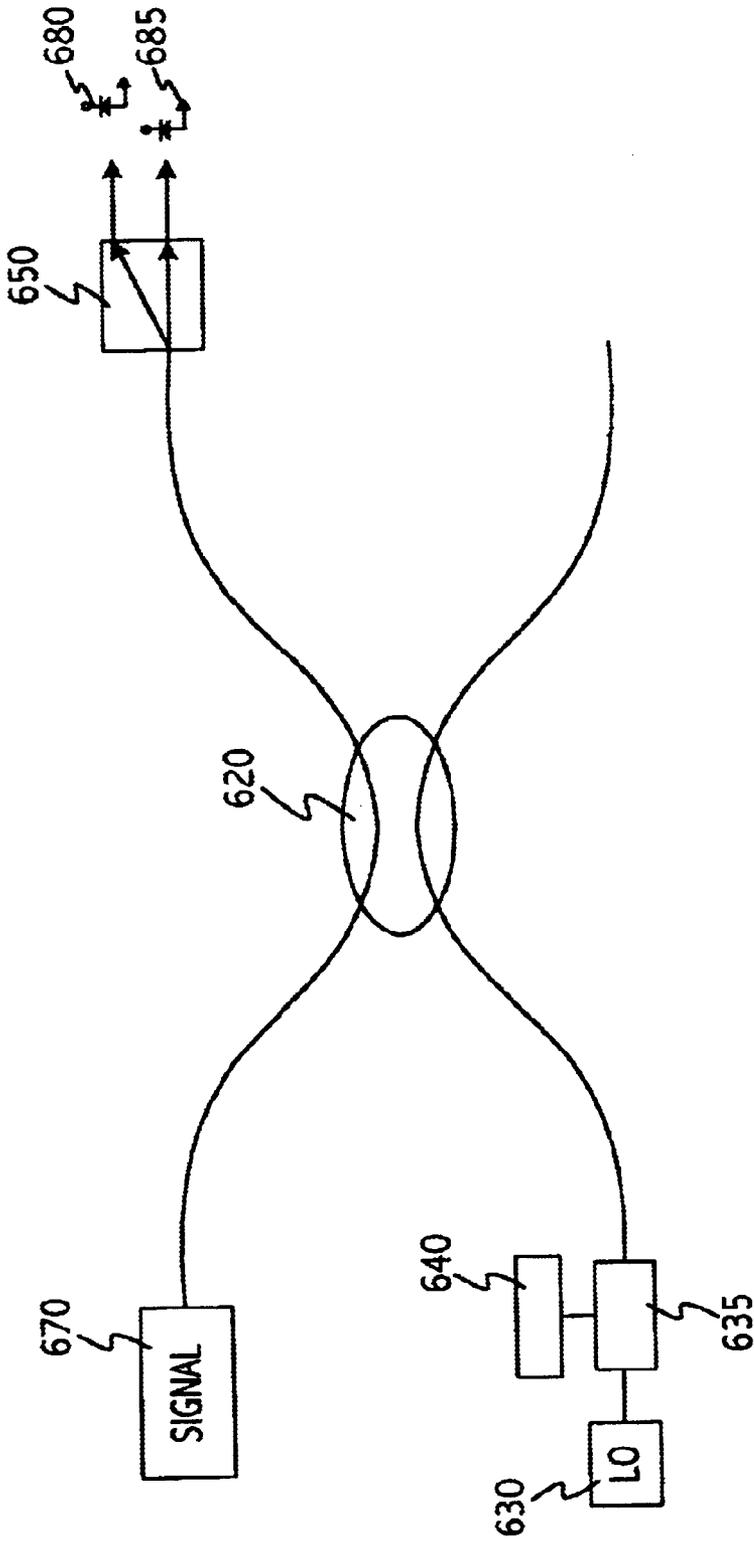
FIGURE 6B

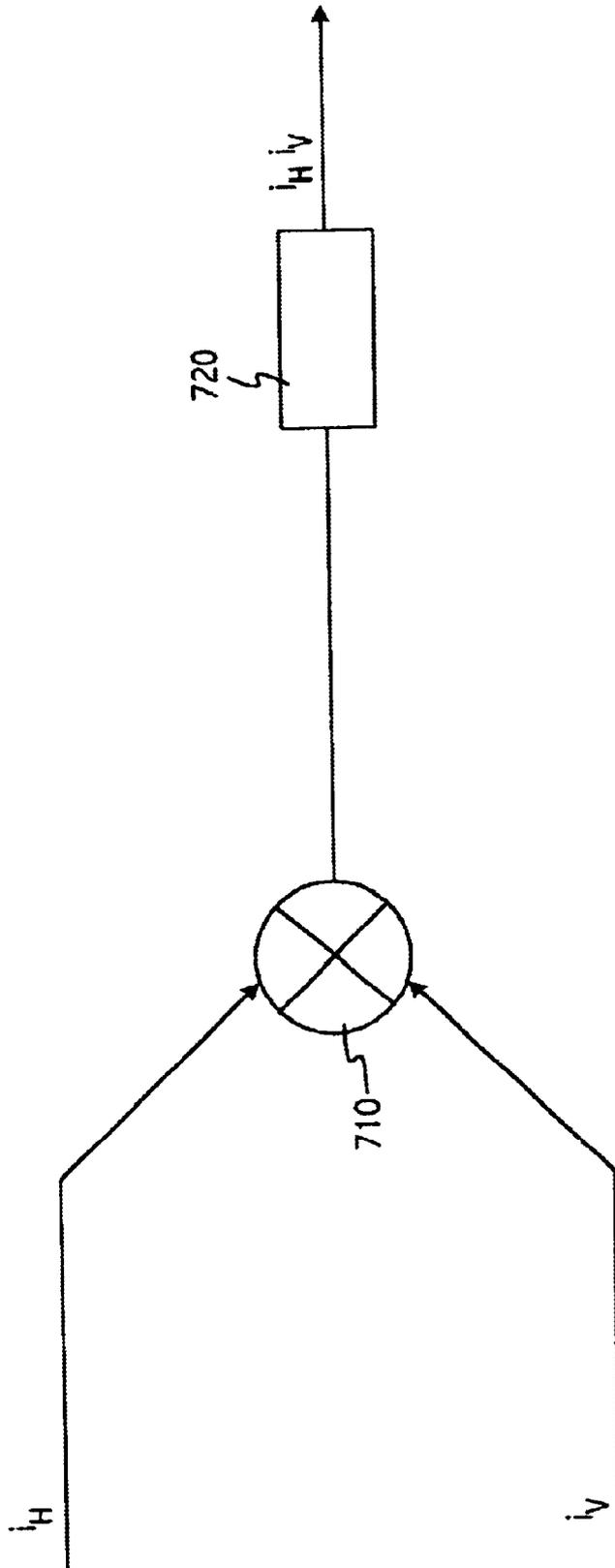FIGURE 7
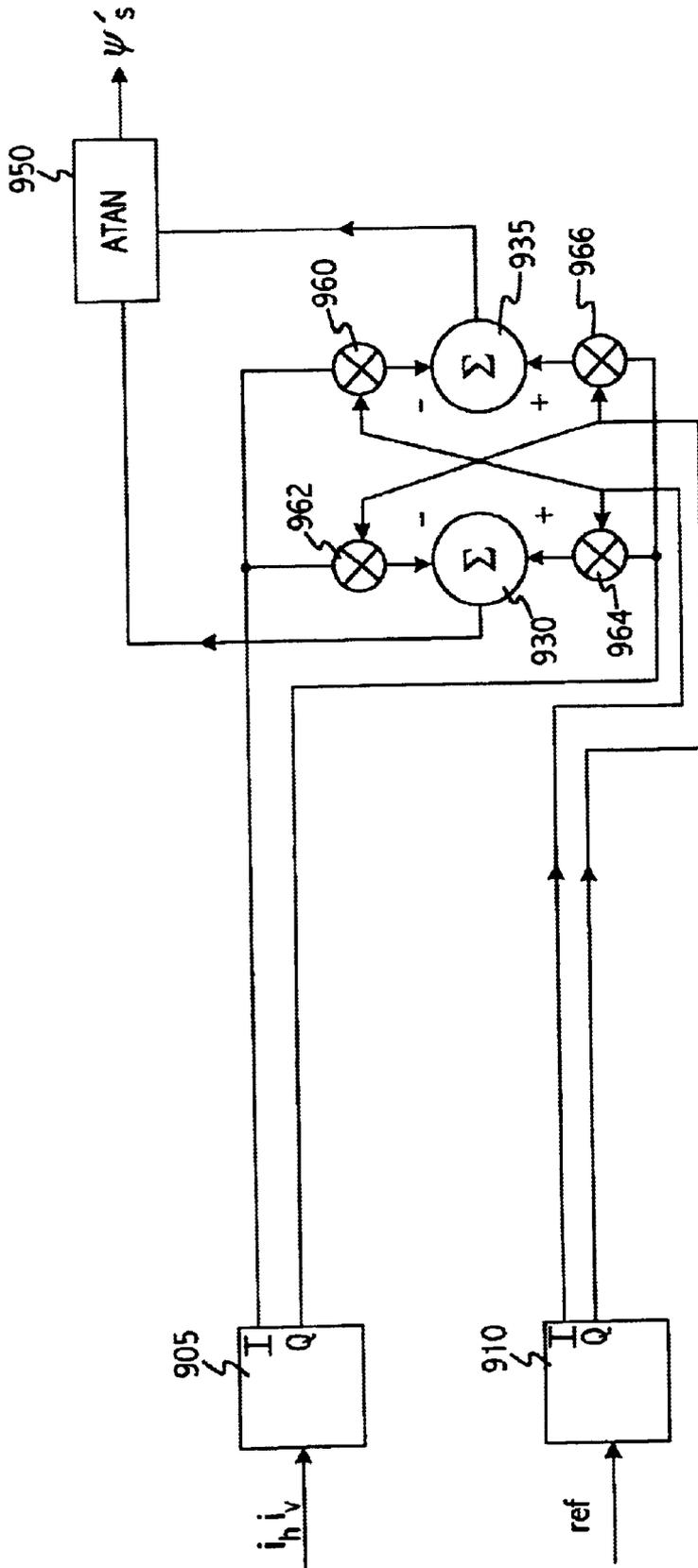
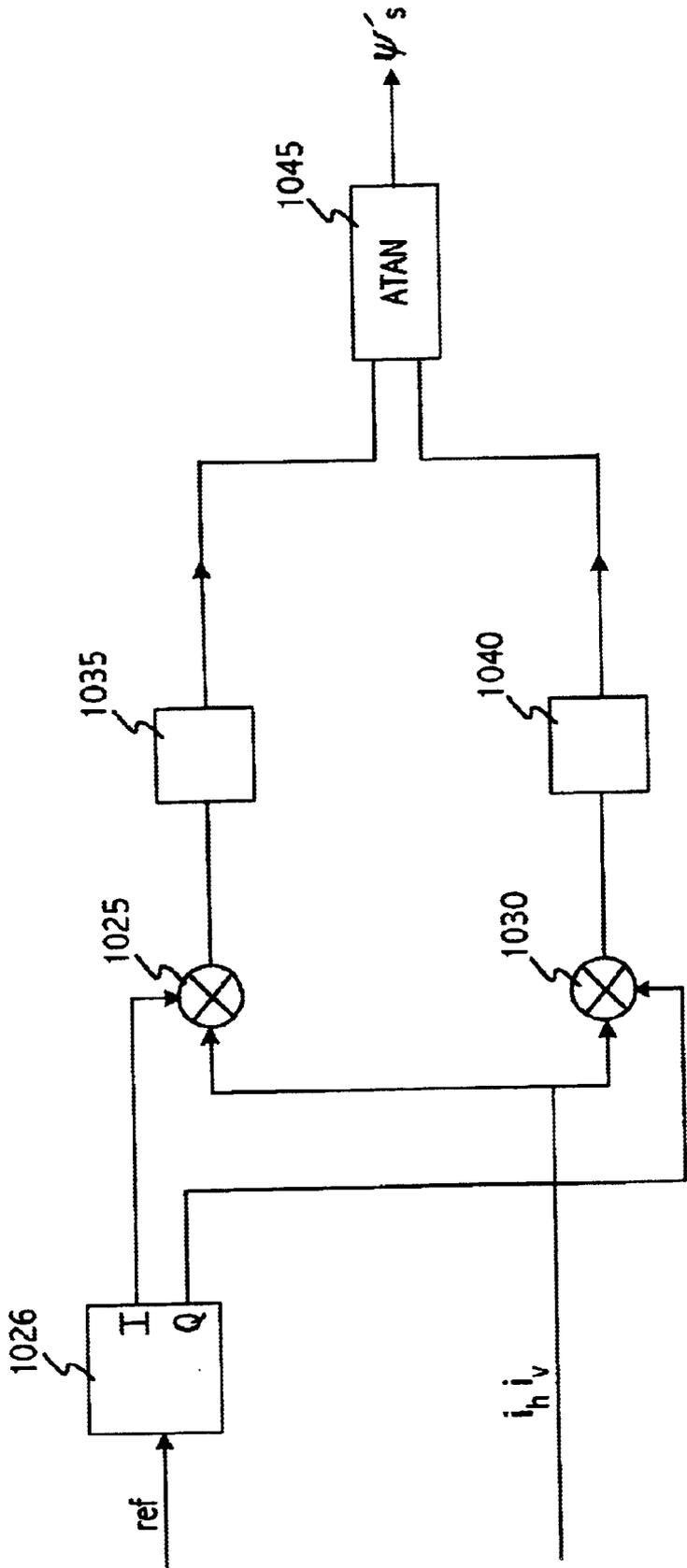FIGURE 8

FIGURE 9

ψ'_s

1045

ATAN

1035

1040

1025

1030

1026

I

Q

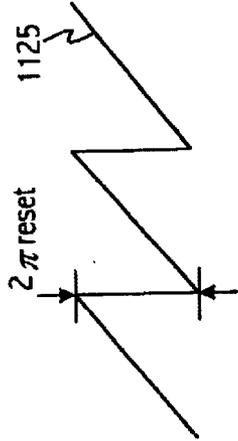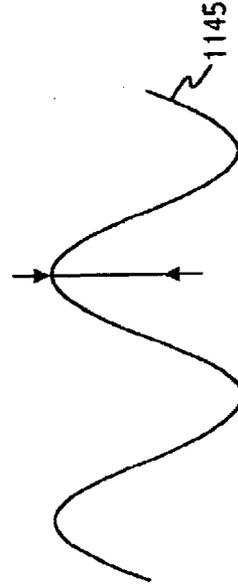ref

$i_h\, i_v$

FIGURE 10
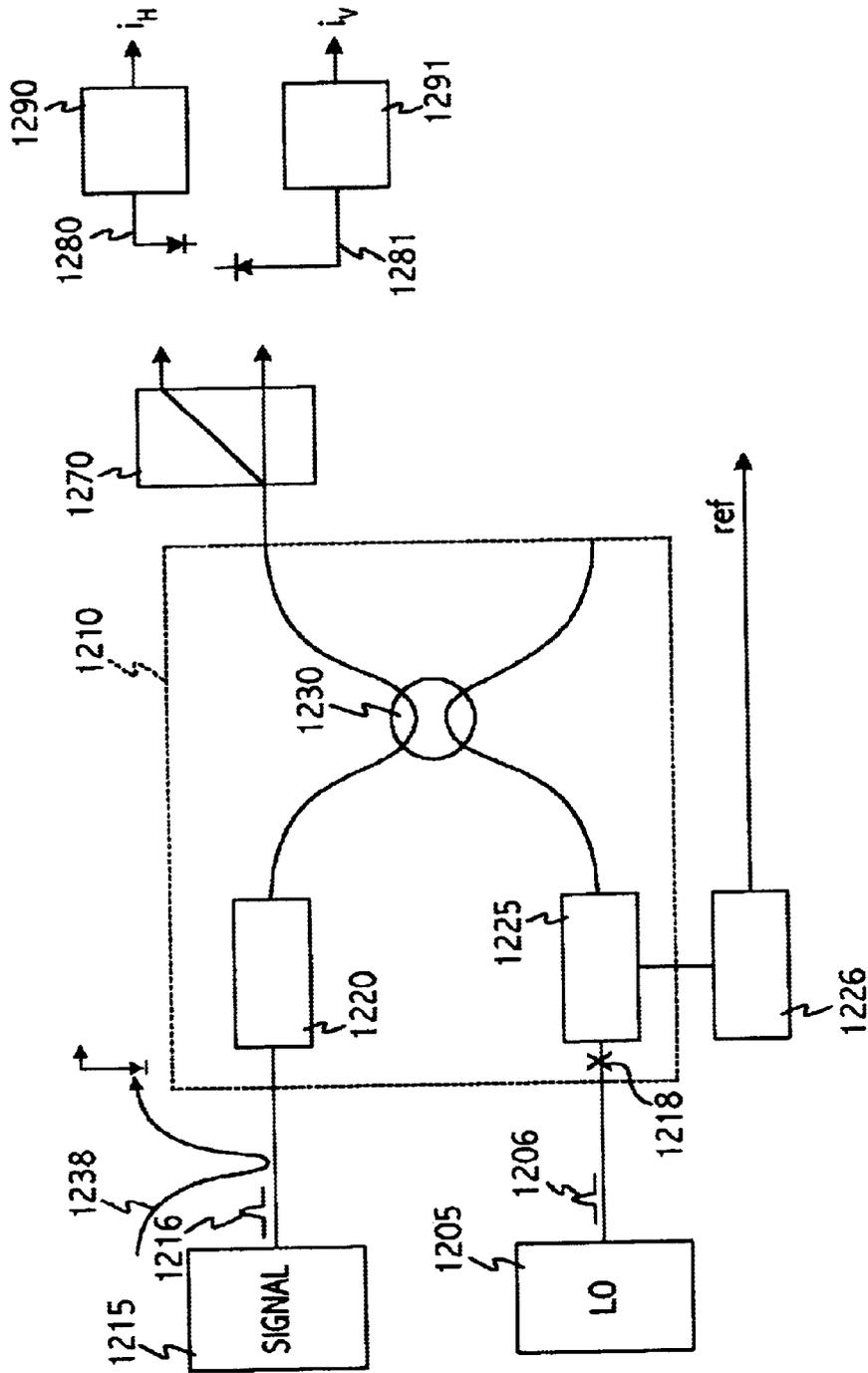
FIGURE 11A

FIGURE 11B

FIGURE 12

METHOD AND APPARATUS FOR A JONES VECTOR BASED HETERODYNE OPTICAL POLARIMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application relates to the copending application Ser. No. 10/271132 (Attorney Reference No: 10020448), filed on the same day, entitled "System and Method for PMD Measurement from Coherent Spectral Analysis" by Szafraniec and Baney owned by the assignee of this application and incorporated herein by reference.

BACKGROUND OF THE INVENTION

Typically, optical polarization state measurement methods are based on measurements of the individual Stokes vector components, i.e., measurements of the optical power transmitted through 0° linear, 45° linear and circular polarizers. The analogous technique has been proposed in the heterodyne architecture by I. Roudas et al. in "Coherent heterodyne frequency-selective polarimeter for error signal generation in higher-order PMD compensators," OFC 2002, pp. 299–301, where the polarization state of the local oscillator is sequentially switched between 0° linear, 45° linear and circular polarization states to provide heterodyne measurements of the signal amplitude in the selectable polarization states. The polarization switching that is required slows down the polarization measurement process.

Another heterodyne technique determines the polarization state by determining the amplitude and relative phase of the two detected heterodyne signals. This technique has been used by K. Oka et al., "Evaluation of phase fluctuations of orthogonal optical eigen modes guided in an axially vibrating birefringent single-mode fiber", Journal of Lightwave Technology, Vol. 8, No. 10, 1482–1486, 1990 to determine fiber birefringence and by C. Chou et al., "Amplitude sensitive optical heterodyne and phase lock-in technique on small optical rotation angle detection of chiral liquid", Japanese Journal of Applied Physics, Part 1, Vol. 36, No. 1A, 356–359, 1997 to measure optical activity in chiral liquids at fixed optical frequencies. However, this heterodyne technique has not been used with swept local oscillator sources.

SUMMARY OF THE INVENTION

An optical heterodyne system is inherently sensitive to the polarization of the heterodyned signals. In accordance with the invention, a polarization state is measured by using a polarization diversity receiver employing a polarization beam splitter to output two heterodyne signals. The amplitude and relative phase of the two detected heterodyne signals uniquely determine the polarization state. However, a problem arises when the local oscillator (LO) is swept over a frequency range and not kept at a fixed frequency. The polarization state is no longer uniquely determined but jumps between the hemispheres of the Poincare sphere creating a polarization state ambiguity.

Modification of the detection method and apparatus in accordance with the invention eliminates the polarization state ambiguity arising from the two images that result from the mixing process thus allowing unambiguous determination of the polarization state.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows grid lines that correspond to constant α and ψ on a Poincare sphere in accordance with the invention.

FIG. 2 shows a heterodyne polarimeter in accordance with the invention.

FIG. 3 illustrates the apparent phase flip between the two hemispheres of the Poincare sphere.

FIG. 4 shows the use of orthogonal filters to determine the inphase (I) and quadrature (Q) components in accordance with an embodiment of the invention.

FIG. 5 shows an embodiment in accordance with the invention for determining the phase difference.

FIG. 6a shows a simplified block diagram of an embodiment in accordance with the invention.

FIG. 6b shows an embodiment in accordance with the invention.

FIG. 7 shows a multiplier module and low pass filter in an embodiment in accordance with the invention.

FIG. 8 shows an embodiment in accordance with the invention which involves spinning the polarization state by using polarization maintaining fiber interferometer.

FIG. 9 shows an embodiment in accordance with the invention for determining the phase difference using the in-phase and quadrature components of $i_H i_V$ and the reference signal.

FIG. 10 shows an embodiment in accordance with the invention for determining the phase difference using $i_H i_V$ and the in-phase and quadrature components of the reference signal.

FIG. 11a shows a saw-tooth modulation signal with 2π phase resets in accordance with the invention.

FIG. 11b shows a sinusoidal modulation signal in accordance with the invention.

FIG. 12 shows an embodiment in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the invention, two parameters of the Jones vector that relate easily to the Poincare sphere are directly measured using a heterodyne optical polarimeter to determine the polarization state of a signal. In the selected formalism, the Jones vector contains the two parameters α and ψ such that the Jones vector for the polarization state P is represented as:

$$P = \begin{pmatrix} \cos\alpha \\ e^{i\psi}\sin\alpha \end{pmatrix}. \tag{1}$$

The angles α and ψ do not correspond to the two parameters, azimuth and ellipticity, typically used in connection with the Poincare sphere. FIG. 1 shows grid lines that correspond to constant α and ψ on Poincare sphere 100. The parameter α specifies a circle in the vertical plane. The parameter ψ specifies a locus on that circle which corresponds to a polarization state. The parameter ψ may be viewed as moving the polarization state on the circle so that the parameter ψ is the polarization state phase. Hence, control of the parameter ψ corresponds to control of the polarization phase with each vertical circle defined by the parameter α. With reference to FIG. 1, to determine the polarization state, P, described by Eq. (1) on Poincare sphere 100, the angle 2α is measured by moving counterclockwise along equator 125 from linear horizontal polarization state 110 as shown in FIG. 1. The angle ψ is measured by moving counterclockwise about the axis V-H where V (not shown) is the linear vertical polarization state on the opposite side of the

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Poincare sphere from H **110**. For example, right circular polarization state **120** is located at a pole of Poincare sphere **100** as shown in FIG. **1** and is reached by moving $2\alpha=\pi/2$ along equator **125** from H **110** and then moving counterclockwise $\psi=\pi/2$ about the axis V-H. Therefore, the Jones vector R for the right circular polarization state is:

$$R = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ i \end{pmatrix} \tag{2}$$

FIG. **2** shows a typical basic architecture for heterodyne polarimeter **210**. It is assumed that coupler **220** does not alter the polarization state by taking the birefringence to be negligible. The polarization state of LO **230** is selected to provide substantially equal power at photodetectors **280** and **285**. This corresponds to a set of polarization states defined by great circle **140** about the axis V-H of Poincare sphere **100** as shown in FIG. **1**. Great circle **140** contains the 45° linear polarization state and circular polarization states R and L. Typically, LO **230** is swept such that its frequency $\omega(t)=\omega_o+2\pi\gamma t$ where γ is the sweep rate. Hence the phase of LO **230**, ϕ_o, is found as $\phi_o=\int\omega(t)dt=\pi\gamma t^2+\omega_o t$. The LO amplitude is a_0 and the LO phase is ξ_0.

Typically, ξ_0 contains phase noise. Using the notation from Eq. (1), the electric field of LO **230** is given by:

$$E_0 = a_0\exp(i\pi\gamma t^2 + i\omega_0 t + \xi_0)\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ e^{i\psi_0} \end{pmatrix} \tag{3}$$

For signal **270** whose polarization state is taken to be arbitrary:

$$E_s = a_s\exp(i\omega_s t + \xi_s)\begin{pmatrix} \cos\alpha_s \\ e^{i\psi_s}\sin\alpha_s \end{pmatrix} \tag{4}$$

where a_s is the amplitude of signal **270**, ω_s is the frequency of signal **270** and ξ_0 is the phase of signal **270** including the phase noise contribution. The polarization state of signal **270** is determined by the angles α_s and ψ_s. The orthogonal linear components of the combined signal and LO **230** are detected individually after passing through polarizing beam splitter **250** (see FIG. **2**):

$$E_{H,V}=P_{H,V}(E_o+E_s), \tag{5}$$

where

$$P_H =\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \text{ and } P_V =\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

are Jones matrices for the horizontal and vertical linear polarizers realized by polarizing beam splitter **250**, respectively. The splitting ratio and phase shift due to optical coupler **320** are omitted for clarity. The intensity at photodiodes **380** and **385** is given by

$$I_{H,V} = E_{H,V}^T \cdot E_{H,V}^*,$$

respectively. For a typical Gaussian low-pass receiver, the heterodyne beat signals corresponding to the detected horizontal and vertical polarization states are given by:

$$i_H=\alpha_o\alpha_s\cos\alpha_s\cos(\pi\gamma t^2+\xi_o-\xi_s)\exp(-t^2/\tau^2) \tag{6}$$

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and

$$i_V=\alpha_o\alpha_s\sin\alpha_s\cos(\pi\gamma t^2+\xi_o-\xi_s+\psi_o-\psi_s)\exp(-t^2/\tau^2), \tag{7}$$

where τ represents the time required to sweep the 1/e half-bandwidth of the Gaussian low-pass receiver at the sweep rate γ.

To simplify the mathematical notation, it is assumed that that the responsivity of photodiodes **280** and **285** is unity and at t=0 the frequencies ω_o and ω_s are equal, hence $\omega_s=\omega_o$. Eqs. (6) and (7) are oscillatory functions whose amplitudes and phases are related by the angles α_s and ψ_s that describe the polarization state of signal **270**. The relative amplitudes of Eqs. (6) and (7) determine the angle α_s because $\tan\alpha_s=|i_V|/|i_H|$ and the phase difference between Eqs. (6) and (7) determines the angle ψ_s with respect to ψ_o because $\psi_s-\psi_o=\arg(i_V)-\arg(i_H)$ where arg is defined to be the argument of the cosine function. Because the polarization state is determined with reference to the polarization state of LO **230** which is assumed to be constant during the measurement procedure, it is convenient to introduce the angle $\psi'_s=\psi_s-\psi_o$. The phase noise of LO **230** and signal **270** is represented by the term $\xi_o-\xi_s$ which appears in the cosine arguments of Eqs. (6) and (7) and cancels when the phase difference between signals i_H and i_V is considered. Measurement of the relative amplitude and phase difference of the signals i_H and i_V determines the parameters α_s, ψ and thereby the relative polarization state:

$$P_{s-o} =\begin{pmatrix} \cos\alpha_s \\ e^{i\psi_s}\sin\alpha_s \end{pmatrix} \tag{8}$$

Power from LO **230** is taken to be split equally between the two detected polarization states to simplify the analysis.

Typically, amplitude and phase may be recovered from the oscillatory signals using orthogonal filters. Note that the heterodyne beat frequency changes quadratically with time as shown in FIG. **3**. FIG. **4** shows the use of orthogonal filters **410** and **420** to determine the in-phase (I) and quadrature (Q) components and therefore, the amplitude (R) and phase (Θ) of the signals i_H and i_V, respectively, for heterodyne polarimeter **210**. The recovered phase from i_H is inverted and added to the recovered phase from i_V by summation module **430** to calculate the phase difference, ψ'_s. The recovered amplitudes from i_H and i_V are then processed to obtain the angle α from arctangent module **440**. Orthogonal filters **410**, **420** and modules **430**, **440** in FIG. **4** are typically incorporated into a signal processor unit, such as processor **690** in FIG. **6a**.

FIG. **5** shows an embodiment in accordance with the invention for determining the phase difference, ψ'_s which is typically more robust than that shown in FIG. **4**. Angle α is determined as in FIG. **4** using arctangent module **540**. The phase difference, ψ'_s, in FIG. **5** is determined from the in-phase and quadrature components of i_H and i_V which are obtained using quadrature filters **510** and **520**, respectively. The in-phase component of the i_H heterodyne beat signal is multiplied by the quadrature component of the i_V heterodyne beat signal in multiplier module **562** and inverted. The quadrature component of the i_H heterodyne beat signal is multiplied by the in-phase component of the iv heterodyne beat signal in multiplier module **564**. The two signals are then combined in summation module **530** to yield $\sin\psi'_s$ which is input to arctangent module **550**. The in-phase component of the i_H heterodyne beat signal is multiplied by the in-phase component of the i_V heterodyne beat signal in multiplier module **560**. The quadrature component of the i_H

heterodyne beat signal is multiplied by the quadrature component of the i_V heterodyne beat signal in multiplier module **566**. The two signals are then combined in summation module **535** to yield cos ψ'_s which is input to arctangent module **550**. Arctangent module **550** outputs the phase difference, ψ'_s. Quadrature filters **510, 520** and modules **540, 550, 562, 560, 530, 535, 564, 566** are typically part of a signal processor unit such as processor **690** in FIG. **6a**.

The quadratic phase behavior resulting from swept LO **230** in heterodyne receiver **210** creates a hemisphere uncertainty because of the apparent phase reversal that occurs when $\Delta\omega$, the frequency difference between swept LO **230** and signal **270**, changes sign as the local oscillator frequency is swept past the signal frequency. For a band-pass receiver centered at the intermediate frequency (IF), ω_{IF}, the heterodyne beat signal at that frequency appears when $\Delta\omega=\omega_o-\omega_s=\omega_{IF}$ and when $\Delta\omega=\omega_s-\omega_o=\omega_{IF}$ where ω_o is the LO optical frequency and ω_s is the signal optical frequency. This leads to two images that have opposite sign of the polarization phase ψ'_s. The analogous behavior exists for negative and positive frequencies in a low-pass receiver. This is shown in FIG. **3**. FIG. **3** shows heterodyne beat signals **310** and **320**, typically corresponding to the detected horizontal and vertical polarization states typically defined by a polarizing beam splitter. For $\Delta\omega<0$, beat signal **320** has phase lag **315** with respect to beat signal **310** while for $\Delta\omega>0$, beat signal **320** has phase lead **316** with respect to beat signal **310**, indicating an apparent phase flip.

The apparent change in the sign of ψ'_s corresponds to a jump from one hemisphere of Poincare sphere **100** to the other. If a polarization state measurement is performed on a signal source having a linewidth narrower than the receiver bandwidth the sign uncertainty may be avoided by examining only the left or right hand image. If a signal source has a linewidth wider than the receiver bandwidth, the measured signal continuously jumps between the left and the right image or the measured signal's spectral components forming the left image counteract the spectral components forming the right image. Hence, a measurement of the polarization state is typically only possible for polarization states on or near equator **125** of Poincare sphere **100**. Several approaches may be used to overcome the problem of hemisphere uncertainty. Typically, implicit in the approaches to removing the hemisphere uncertainty is measuring the product of the i_V heterodyne beat signal with the i_H heterodyne beat signal since the product is invariant to changes in the sign of ψ'_s. This approach requires the introduction of a reference signal to allow determination of the phase, ψ'_s. In accordance with the invention, other non-linear operators besides the product $i_H i_V$ produce a similar result. For example, any operations yielding a product in the power series expansion: $f(xy)=f(0)+f'(0)xy+\frac{1}{2}f''(0)x^2y^2+\ldots$ where f is a suitable function may be used.

FIG. **6a** shows a simplified block diagram of an embodiment in accordance with the invention. Tunable LO block **630** is coupled to polarization phase controller block **625** which is coupled to polarization diversity receiver block **615**. Signal source block **610** supplies the external optical signal to be measured and is also coupled to polarization diversity receiver block **615**. Polarization diversity receiver block **615** combines the local oscillator signal with the external optical signal and detects two, typically, linearly orthogonal heterodyne components which are processed by processor **690** to determine the polarization of the external signal.

FIG. **6b** shows an embodiment in accordance with the invention. The embodiment is similar to that shown in FIG.

2 but polarization phase controller **635** and modulation signal generator **640** have been added to provide polarization phase control and a reference signal for the signal analysis. Note that modulation signal generator **640** provides a reference signal to processor **690** (see FIG. **6a**). The receiver is typically taken to be a band-pass receiver that rejects DC. The angle ψ_0 of the polarization state of LO **630** can be shifted by a known phase shift $\Delta\psi$ using polarization controller **635**. The phase shift $\Delta\psi$ corresponds to moving by an angle $\Delta\psi$ on great circle **140** on Poincare sphere **100**. Phase shifts may typically be induced into the signal coming from LO **630** by using Ti-indiffused LiNbO$_3$ phase modulator **635** oriented at 45° with respect to the linear polarization state of the signal from LO **630** or by any other means of changing ψ such as a polarization controller. The phase shift $\Delta\psi$ is typically controlled by modulation voltage **640** applied to phase modulator **635**. Optical coupler **620** combines signal **670** and the signal from LO **630**. Photodiodes **680** and **685** detect the orthogonal linear components of the combined signal **670** and signal from LO **630** individually after passing through beam splitter **650**. This results in electrical signals i_H and i_V which are then processed further by examining the hemisphere invariant product $i_H i_V$ as well as the individual signals i_H and i_V.

In accordance with an embodiment of the invention, two separate measurements are performed using phase shifts $\pm\Delta\psi_0/2$, respectively. With reference to FIG. **7**, signals i_H and i_V are first multiplied together in multiplier module **710** and then low-pass filtered by low-pass filter **720**. Because signals i_H and i_V are both at the same frequency, the multiplication of the two signals results in a DC term that is measured and an AC term that is rejected by low-pass filter **720**. Module **710** and low-pass filter **720** are typically implemented in a signal processor, such as processor **690** in FIG. **6**.

Multiplication of signal i_H by signal i_V yields a DC and an AC term. Note that the product, $i_H i_V$, is hemisphere invariant and removes the hemisphere uncertainty discussed above. Considering the DC term for a phase shift of $\Delta\psi_0/2$ gives:

$$p_1=A\cos(\psi'_s+\Delta\psi_0/2) \tag{9}$$

where A is typically a time varying amplitude. Considering the DC term for a phase shift of $-\Delta\psi_0/2$ gives:

$$P_2=A\cos(\psi'_s-\Delta\psi_0/2) \tag{10}$$

Eqs. (9) and (10) may be used to determine ψ'_s:

$$\tan(\psi'_s)\tan(\Delta\psi_0/2) = \frac{p_2-p_1}{p_1+p_2} \tag{11}$$

which simplifies to:

$$\tan(\psi'_s) = \frac{p_2-p_1}{p_1+p_2} \tag{12}$$

when $\Delta\psi_0=\pi/2$. The introduction of reference angles $\pm\Delta\psi_0/2$ using Ti-indiffused LiNbO$_3$ phase modulator **635** allows recovery of the phase ψ'_s. In this embodiment, the reference signal is simply the phase shift, $\Delta\psi$.

In accordance with an embodiment of the invention, the hemisphere uncertainty may be removed by using a swept local oscillator (LO) to provide a signal comprising two optical frequencies separated by $\Delta\omega$ and having orthogonal linear polarization states. FIG. **8** shows an embodiment in

accordance with the invention which involves spinning the polarization state by using polarization maintaining fiber interferometer **817** to provide polarization phase control and a reference signal. LO **810** outputs frequency swept linearly polarized optical signal **811** and is aligned with and coupled to polarization maintaining optical fibers **820** and **825** by optical coupler **815**. Splice **850** is typically a 90° splice in polarization maintaining fiber **820**. Arm imbalance **845** introduces delay τ_d which results in a frequency shift, $\Delta\omega=-2\pi\gamma\tau_d$, in LO signal **805** in polarization maintaining fiber **825**. When LO optical signals **805** and **806** enter optical combiner **855**, LO signals **805** and **806** are in orthogonal linear polarization states and are shifted in frequency by $\Delta\omega$ with respect to each other as described by Eq. (13). Hence, LO signal **807** has two linear polarization states. In Jones vector notation, this gives for the electric field of LO signal **807** in FIG. **8**:

$$E_0 = a_0 \exp(i\pi\gamma t^2 + i\omega_0 t + \xi_0) \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{i\psi_0 + \Delta\omega t} \end{pmatrix} \qquad (13)$$

where $\Delta\omega$ is the optical frequency shift, $\psi_0 = \pi\gamma\tau_d^2 - \omega_0\tau_d + \phi_1$ where ϕ_1 is the phase difference between optical fibers **820** and **825** and the remaining variables are as defined above.

Optical LO signal **807** is pseudo-depolarized. This means that the polarization state of LO signal **807** spins about Poincare sphere **100** on great circle **140** at a frequency of $\Delta\omega$. Optical coupler **897** combines signal **870** with combined LO signal **807**. The two linearly polarized components of combined LO signal **807** are aligned with polarizing beam splitter **875** so that the polarized components are separated by polarizing beam splitter **875** and separately detected by detectors **880** and **881**. Hence, detector **880** typically detects the LO component that is frequency shifted $\Delta\omega$ from the LO component detected by detector **881**.

Taking Eq. (13) describing the LO electric field E_0, together with Eq. (4) describing the electric field E_s of signal **870**, equations analogous to Eqs. (6) and (7) may be derived using the procedure described above:

$$i_H = 2a_0 a_s \cos(\alpha_s)\cos(\pi\gamma t^2 + \xi_0 - \xi_s)\exp(-t^2/\tau^2/\tau^2) \qquad (14)$$

$$i_V = 2a_0 a_s \sin(\alpha_s)\cos(\pi\gamma t^2 + \Delta\omega t + \xi_0 - \xi_s + \psi_0 - \psi_s)\exp(-t^2/\tau^2). \qquad (15)$$

Therefore, using Eqs. (14) and (15) the low-pass-filtered hemisphere independent product $i_H i_V$ is given by:

$$p = A \cos(\psi'_s + \Delta\omega t). \qquad (16)$$

The low-pass-filtered product p in Eq. (16) may typically be found as shown in FIG. **7**. The product $i_H i_V$ of Eq. (16) represents an oscillatory function with a frequency of $\Delta\omega$ and a phase shift of ψ'_s. Polarization modulated LO signal **808** also passes through 45° polarizer **890** and is detected by detector **891** which converts optical signal **808** to an electrical signal that is typically low-pass-filtered by low-pass filter **895** to output a reference signal ref proportional to $\cos(\Delta\omega t + \psi_0)$. Derivation of a $\cos(\Delta\omega t + \psi_0)$ reference signal, ref, from LO signal **808** using interferometer **817** allows the phase shift ψ_s ($\psi'_s = \psi_0 - \psi_s$) to be determined, for example, using the phase sensitive detection techniques shown in FIG. **9** or FIG. **10**. Low-pass filter **895** is typically implemented in a signal processing unit such as processor **690** in FIG. **6a**.

With reference to FIG. **9**, the phase difference, ψ_s, is determined from the in-phase and quadrature components of $i_H i_V$ and the reference signal, ref, from quadrature filters **905** and **910**, respectively. The in-phase component of the $i_H i_V$ heterodyne beat signal is multiplied by the quadrature com-

ponent of the reference signal in multiplier module **962** and inverted. The quadrature component of the $i_H i_V$ heterodyne beat signal is multiplied by the in-phase component of the reference signal in multiplier module **964**. The two signals are then combined in summation module **930** to give $\sin(\psi_s)$ and input to arctangent module **950**. The in-phase component of the $i_H i_V$ heterodyne beat signal is multiplied by the in-phase component of the reference signal in multiplier module **960**. The quadrature component of the $i_H i_V$ heterodyne beat signal is multiplied by the quadrature component of the reference signal in multiplier module **966**. The two signals are then combined in summation module **935** to give $\cos(\psi_s)$ and also input to arctangent module **950**. Arctangent module **950** outputs the angle for signal **870**, ψ_s. Quadrature filters **905**, **910** and modules **962**, **960**, **930**, **935**, **964**, **966**, **950** are typically implemented in a signal processing unit, such as processor **690** in FIG. **6a**.

Alternatively, with reference to FIG. **10**, the phase difference, ψ_s, may be determined using $i_H i_V$ and the in-phase and quadrature components of reference signal, ref from quadrature filter **1020**. The in-phase component of reference signal, ref, is multiplied by $i_H i_V$ in multiplier module **1025** prior to low-pass filtering by low-pass filter **1035**. The quadrature component of reference signal, ref, is multiplied by $i_H i_V$ in multiplier module **1030** prior to low-pass filtering by low-pass filter **1040**. The outputs from filter modules **1035** and **1040** are the cosine and sine of ψ_s, respectively, which are input into arctangent module **1045** to recover the angle for signal **870**, ψ_s. Quadrature filter **1020**, modules **1025**, **1030**,**1045** and low-pass filters **1035** and **1040** are typically implemented in a signal processor such as processor **690** in FIG. **6a**.

Other embodiments in accordance with the invention are possible for spinning the polarization state besides the embodiment shown in FIG. **8**. For example, the embodiment shown in FIG. **6b** achieves depolarization using Ti-indiffused LiNbO₃ phase modulator **635**. Modulation signal generator **640** in this embodiment may be set to saw-tooth modulation **1125** with 2π phase resets as shown in FIG. **11a**, where phase refers to a phase difference between the transverse electric and transverse magnetic mode . The polarization spinning is discontinuous. The polarization state makes a complete rotation about Poincare sphere **100** on great circle **140** and resets to the starting position to repeat the rotation.

An embodiment in accordance with the invention is shown in FIG. **12**. Ti-in-diffused LiNbO₃ phase modulator device **1210** functions to depolarize LO signal **1206** from LO **1205**, combine signal **1216** and LO signal **1206** in optical combiner **1230** and, if desired, modulate signal **1216** in optional signal phase modulation unit **1220**. Note that Ti-indiffused LiNbO₃ phase modulator **1225** is coupled to LO **1205** at junction **1218** so that the axes of birefringence of phase modulator **1225** are oriented at 45° with respect to the linear polarization state of LO **1205**. The embodiment shown in FIG. **12** has an optional provision for intensity noise subtraction. The intensity noise monitor module **1238** typically allows for reduction of noise using Kalman filtering as disclosed in "Kalman Filter Intensity Noise Subtraction for Optical Heterodyne Receivers" by Szafraniec, attorney docket no. 10020440-1 and incorporated by reference.

Polarizing beam splitter **1270** is typically attached directly to Ti-in-diffused LiNbO₃ phase modulator device **1210** at 45° to equalize the power from LO **1205** at detectors **1280** and **1281**. When the embodiment is used as a heterodyne optical spectrum analyzer, polarization diversity is provided both by depolarization of LO reference signal **1206** and

through the use of polarizing beam splitter **1270** to provide dual polarization diversity. This is typically advantageous as single stage polarization diversity typically is only about 95% effective. Photodiodes **1280** and **1281** detect the two optical components i_H and i_V, respectively, from polarizing beam splitter **1270**. Preamplifiers **1290** and **1291** amplify the electrical signals from photodiodes **1280** and **1281**, respectively. The parameter ψ which corresponds to the polarization phase is measured using the embodiment in accordance with the invention shown in FIG. **9** or FIG. **10**. The reference signal, ref, is provided by modulation signal generator **1226** to processor **690** (see FIG. **6**a).

With reference to FIG. **12** or FIG. **6**b, sinusoidal modulation **1145** shown in FIG. **11**b may be used in place of sawtooth modulation **1125** (see FIG. **11**a) as the modulation waveform in an embodiment in accordance with the invention. Sinusoidal modulation **1145** causes the polarization state to move about the phase ψ_0 on great circle **140** of Poincare sphere **100**. With sinusoidal modulation **1145**, the low-pass filtered product $i_H i_V$ becomes:

$$p = A \cos(\psi'_s + \alpha \cos(\omega_m t)) \tag{17}$$

where a is the modulation depth and ω_m is the modulation frequency. The modulation depth, a, depends on the difference in the electro-optic coefficients that describe the change in refractive index of the TE and TM mode in response to the applied voltage to Ti-indiffused $LiNbO_3$ phase modulator unit **1225**. Modulation depth, a, can be adjusted by changing the amplitude of the applied sinusoidal waveform so that LO **1205** is pseudo-depolarized. An appropriate series expansion of Eq. (17) gives:

$$p = AJ_0(a)\cos(\psi'_s) - \tag{18}$$
$$2AJ_2(a)\cos(2\omega_m t)\cos(\psi'_s) +$$
$$2AJ_4(a)\cos(4\omega_m t)\cos(\psi'_s) -$$
$$\vdots$$
$$2AJ_1(a)\cos(\omega_m t)\sin(\psi'_s)$$
$$2AJ_3(a)\cos(3\omega_m t)\sin(\psi'_s) -$$
$$2AJ_5(a)\cos(5\omega_m t)\sin(\psi'_s)$$
$$\vdots$$

In practice, the desired harmonics may typically be isolated by using a spectrum analyzer or a lock-in amplifier. A lock-in amplifier may be used to detect individual selected harmonics and their phase. Measurement of the odd or even harmonic in Eq. (18) for a known modulation depth, a, allows the phase ψ'_s to be found. For example, by using the amplitude of the first harmonic, $h_1 = 2AJ_1(\alpha) \sin(\psi'_s)$ and the amplitude of the second harmonic, $h_2 = -2AJ_2(\alpha) \cos(\psi'_s)$, the angle, ψ'_s may be recovered:

$$\tan(\psi'_s) = \frac{h_1 J_2(a)}{h_2 J_1(a)}. \tag{19}$$

If an electrical spectrum analyzer or Fourier analysis is used to determine h_1 and h_2, their values are always positive. Therefore, the angle ψ'_s obtained from Eq. (19) will always be in the first quadrant while the angle's values range from $-\pi$ to π. Additional quadrant information is typically obtained by comparing the phase of the first and second harmonic signals, for example, with the phase of the reference signal at ω_m and the squared reference signal at $2\omega_m$ in the time domain.

It will be apparent to one skilled in the art that other modulation waveforms besides sinusoidal modulation waveforms can be used in the above embodiment. The only consequence of using a different modulation waveform is that a different harmonic content from that presented in Eq. (18) will be created.

While the invention has been described in conjunction with specific embodiments, it is evident to those skilled in the art that many alternatives, modifications, and variations will be apparent in light of the foregoing description. Accordingly, the invention is intended to embrace all other such alternatives, modifications, and variations that fall within the spirit and scope of the appended claims.

I claim:

1. An optical heterodyne polarimeter for determining the polarization of an optical signal, said optical heterodyne polarimeter comprising:
    a tunable laser source for outputting a swept local oscillator signal;
    a polarization phase controller optically coupled to said tunable laser source to generate a polarization phase shifted swept local oscillator signal from said swept local oscillator signal;
    an optical coupler configured to receive said polarization phase shifted swept local oscillator signal and said optical signal and output a combined signal;
    a polarization diversity receiver optically coupled to said optical coupler to receive said combined signal, said polarization diversity receiver configured to output a first and a second linear polarization component of said combined signal;
    a processor configured to determine the polarization of said optical signal from said first and said second linear polarization components.

2. The optical heterodyne polarimeter of claim **1** wherein said polarization phase controller comprises a Ti-indiffused $LiNbO_3$ phase modulator.

3. The optical heterodyne polarimeter of claim **1** wherein said polarization phase controller generates a shift of 90 degrees.

4. The optical heterodyne polarimeter of claim **2** wherein said Ti-indiffused $LiNbO_3$ phase modulator is oriented at 45 degrees with respect to the linear polarization state of said swept local oscillator signal.

5. The optical heterodyne polarimeter of claim **2** wherein said Ti-indiffused $LiNbO_3$ phase modulator is modulated by a sawtooth waveform.

6. The optical heterodyne polarimeter of claim **2** wherein said Ti-indiffused $LiNbO_3$ phase modulator is modulated by a sinusoidal waveform.

7. The optical heterodyne polarimeter of claim **1** wherein said polarization diversity receiver comprises a polarizing beam splitter.

8. The optical heterodyne polarimeter of claim **1** wherein said polarization phase controller comprises an interferometer for introducing a change of polarization state.

9. The optical heterodyne polarimeter of claim **1** wherein said swept local oscillator signal is pseudo-depolarized.

10. The optical heterodyne polarimeter of claim **1** wherein said processor comprises a quadrature filter.

11. An optical heterodyne polarimeter for determining the polarization of an optical signal, said optical heterodyne polarimeter comprising:
    a local oscillator for outputting a local oscillator signal;
    a polarization phase controller coupled to said local oscillator to modify the polarization state of said local oscillator signal and output a modified local oscillator signal;

a polarization diversity receiver coupled to said polarization phase controller, said polarization diversity receiver having an input to receive said optical signal; and

a processor coupled to said polarization diversity receiver, said processor configured to determine the polarization state of said optical signal.

12. The optical heterodyne polarimeter of claim **11** wherein said local oscillator comprises a tunable laser source.

13. The optical heterodyne polarimeter of claim **12** wherein said tunable laser source generates a swept signal.

14. The optical heterodyne polarimeter of claim **13** wherein said swept signal is pseudo-depolarized.

15. The optical heterodyne polarimeter of claim **11** wherein said polarization phase controller comprises a phase modulator.

16. The optical heterodyne polarimeter of claim **15** wherein said phase modulator is modulated by a sinusoidal modulation signal.

17. The optical heterodyne polarimeter of claim **11** wherein said optical signal is phase modulated.

18. The optical heterodyne polarimeter of claim **11** wherein said polarization phase controller comprises an interferometer.

19. The optical heterodyne polarimeter of claim **11** wherein said optical signal is sampled to enable intensity noise subtraction.

20. A method for making an optical heterodyne polarimeter for determining the polarization of an optical signal comprising:

providing a local oscillator for outputting a local oscillator signal;

providing a polarization phase controller coupled to said local oscillator to modify the polarization state of said local oscillator signal and output a modified local oscillator signal;

providing a polarization diversity receiver coupled to said polarization phase controller, said polarization diversity receiver having an input to receive said optical signal; and

providing a processor coupled to said polarization diversity receiver, said processor configured to determine the polarization state of said optical signal.

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